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Research Article

Design, Development and Evaluation of a Pneumatic cum Eccentric Drive Grain Cleaning Machine: A Response Surface Analysis

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Abstract

Background and Objective: Grain cleaning is still normally carried out by women and children in rural villages. The aim of this study was to design, develop and optimize the conditions necessary for producing clean maize grains by using a response surface modelling method. **Materials and Methods:** Maize (*Zea mays* L. varieties hybrid single cross) was used for this study. Effect of the feed gate openings (13.23, 24.94 and 33.06 mm) and air velocity (9.12, 10.21 and 12.3 m sec^{-1}) on the performance efficiencies (separating loss, cleaning loss and separation efficiency) was studied. **Results:** The performance efficiencies (separation loss, cleaning loss and cleaning efficiency) evaluated were significantly ($p<0.05$) affected by feed gate opening and air velocity used with correlation coefficients $R^2 = 0.803$, 0.799 and 0.814, respectively, whereas the effect was not significant on the separation efficiency with correlation coefficient $R^2 = 0.564$ and the optimal performance efficiencies were obtained by using the desirability function method. The desirability value obtained was 0.986. **Conclusion:** So, it was concluded that the effects of the feed gate opening, air velocity and its optimization were regarded as very useful to ascertain the performance efficiency of the developed grain cleaning machine.

Key words: Grain cleaning, maize, feed gate opening, air velocity, optimization, response surface modeling, performance efficiency

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Maize (*Zea mays*) has turned out to be one of the major cereals in the world after wheat and rice cultivated in sub-saharan Africa, providing nutrient for humans and animal and also serving as a basic raw material in feed mills, starch industries, alcoholic industries and many more[1-3]. The release of high yield varieties combined with the availability of subsidized fertilizer as well as improved infrastructure and extension services contributed to the phenomenal increase in maize production in the country[4]. Most of the important unit operation in which cereal grain undergoes are cleaning, grading, sorting and drying, etc. which helps to reduce significantly the dockage level. Cleaning helps to remove impurities (debris, sand, stone pebbles, chaff and straw, etc.) from grains to enhance its market value and also for further processing operation[5].

After threshing, maize granules still contain some materials other than grains (MOG) which have been noticed to include: sand, small pebbles, plant, insect wastes and seed case, etc. Traditionally, impurities are removed with either rake or broom, while the light contaminants are removed by winnowing. The limitations of traditional method for cleaning are its unpredictable direction, speed and continuity, high labor requirement and a rather non-precise degree of separation[6].

Separation of the good grains from this contaminant will help in upgrading the quality, storage in bins and processing. Some previous work includes; solar-powered pneumatic grain cleaning machine, which utilizes the pneumatic (air) system in blowing unwanted materials, it was reported that the different blade angle was used to regulate the air velocity for garden pea, bottle gourd, sponge gourd and radish[5], cereal grain cleaning machine which utilizes both pneumatic and reciprocating machine which was tested for paddy rice varying different angle of tilt of the sieve casing and at a constant speed[7], auxiliary chickpea second sieving and grading machine which utilizes a reciprocating sieve mechanism for separating impurities from chickpea[8]. From the study, it was observed that the grain cleaning machine which has been developed has not being tested for maize, also the air velocity from the blower has only being regulated with pulleys and blade angle, effect of the feed gate opening on the performance efficiency is also lacking, parameters which affect the performance of the cleaning machine have not been optimized. Therefore, the objectives of the current study were (1) To design and develop a pneumatic cum reciprocating grain cleaner (2) To investigate the influence of air velocity and feed gate opening on the performance efficiency of the grain cleaner using maize-mixture and to optimize the processing conditions for cleaning maize-mixture with the cleaning machine developed and (3) To devise regression models to predict the performance efficiency of the machine as a function of the process variables (air velocity and feed gate opening).

MATERIALS AND METHODS

Materials: This study was organized in Agricultural and Biosystems Engineering Workshop, Landmark University (latitude 8°9°0″N, longitude 5°61°0″E), Omu-Aran, Kwara state, Nigeria, between the period of May-June, 2018. Some freshly harvested threshed maize (*Zea mays* L. Varieties hybrid single cross) from the university farm was used in evaluating the constructed grain cleaner in term of the efficiencies investigated.

Methods: Three levels of Feed gate opening (FGO) (13.23, 24.94 and 33.06 mm) and air velocity (AV) (9.12, 10.21 and 12.3 m sec^{-1}) were used in the evaluation. The grain cleaner was designed taking into cognizance the differences in the aerodynamic properties of maize. The physical properties of the grains were taking into consideration in the screen selection for the reciprocating unit.

Machine component parts: The machine comprises of the following components: A machine frame; use for holding other component and stabilizing the machine during operation, the centrifugal blower is a radial blade type fitted into a squirrel-cage casing for setting cushion of air in motion as in Fig. 1, the hopper was trapezoidal in shape use for feeding the cleaning/separation unit, screen casing contains the reciprocating screens on a different slope and this is the point where the separation was carried out, driving and driven assembly for driving other components of the machine using a 2 hp electric motor and a discharge outlet for clean seed.

Machine analysis

Screen characteristics: Screens are characterized by parameters such as; shape, the effective size of the opening diameter D and the coefficient of opening[7] C_o:

$$C_o = \frac{\text{Open area}}{\text{Total area}} \tag{1}$$

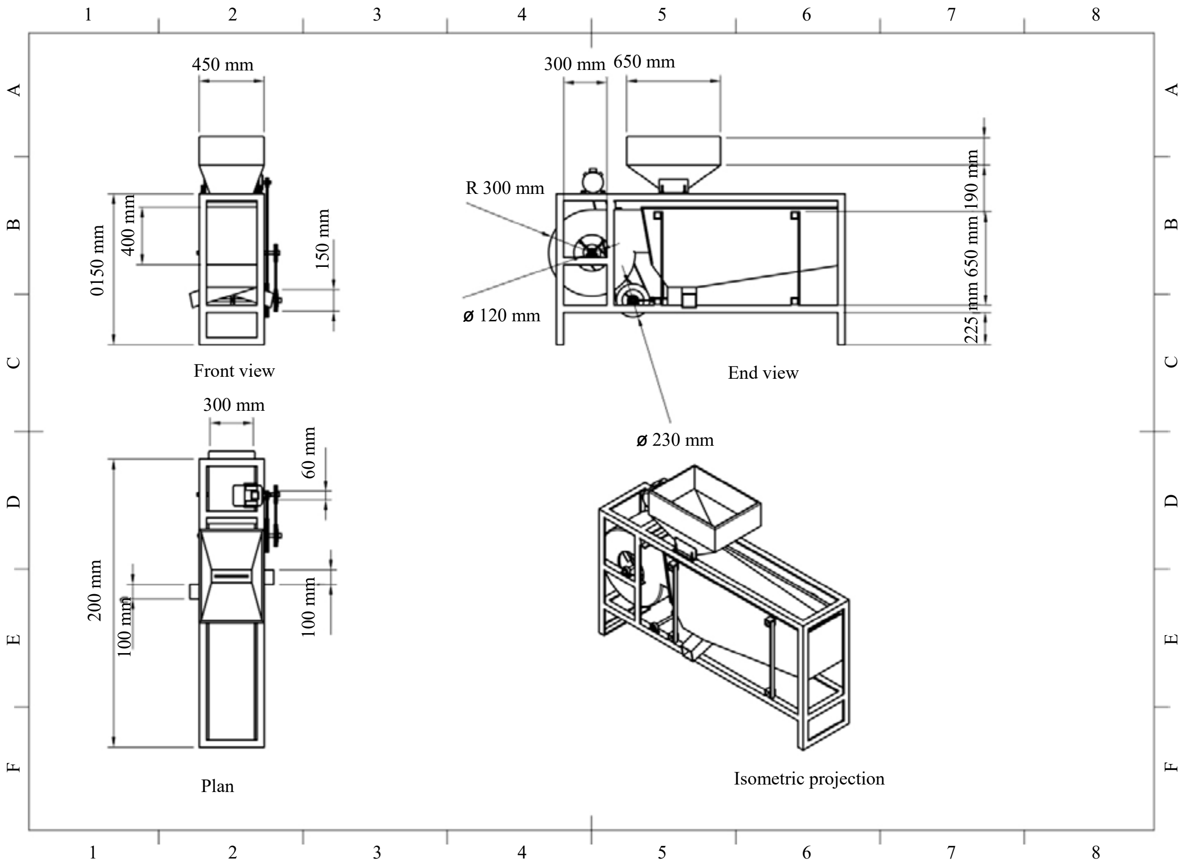

Fig. 1: Orthographic view of the developed grain cleaning machine

The coefficient of the opening (C_o) is taken as 40%. For circular opening:

$$C_o = \frac{3\pi}{2}\times\frac{D^2}{(D+d)^2} \quad (2)$$

where, D is the diameter of the opening, d is the distance between the two successive holes. A circular screen was used for maize for the top and bottom screen. Particle movement on the screen was computed by using the following equation:

$$S = R(1 - \text{Cos}\ \omega t) \pm \frac{R}{4L}\ \text{Cos}2\omega t \quad (3)$$

$$R\omega^2\ \cos\omega t\ \cos\alpha\ (\cos\beta + \mu\sin\beta) \geq \mu g \quad (4)$$

$$\mu = \tan\phi$$

$$R\omega^2\ \cos\omega t\ \cos\alpha\ (\cos\beta - \mu\sin\beta) \geq \mu g \quad (5)$$

where, R is the radius of eccentricity = 0.025 m, ω is the angular speed of rotation = 39.79 rad sec^{-1}, t is the time (sec), L is the connecting rod length, S is the distance moved by the particle, μ is the coefficient of friction = 0.35, β is the angle of suspension = 0°, α is the angle of tilt which was taken as 4°and 15°for the top and bottom screen, respectively.

Shaft speed determination: In determining the speed of the driven shaft (Eq. 7) was used[1]:

$$N_mD_m = N_vD_v \quad (6)$$

where, N_m speed of the driving pulley (prime mover) was 1460 rpm, D_m diameter of the driving pulley (prime mover) was 60 mm, N_v speed of the driven pulley of the eccentric mechanism was 380.9 rpm and for the centrifugal blower was 1111 rpm, D_v diameter of the driven pulley for the eccentric mechanism was 230 mm and for the centrifugal blower was 60 mm.

Velocity of the belt drive: The velocity of the belt drive (V) for the eccentric mechanism and the blower:

$$V = 2\pi N \quad (7)$$

where, N is the speed of the driven pulley.

Power requirement: In calculating the power requirement, the vertical and the horizontal displacement of the reciprocating assembly was considered.

The power requirement, as well as the torque was calculated by using this equation[9]:

$$P = 2\pi NT \tag{8}$$

where, N is the speed and T is the torque.

$$T = F\times r \tag{9}$$

where, F is the force transmitted by the prime mover and r is the perpendicular distance.

Belt length determination: The belt length was deduced[10] by using Eq. 11:

$$L = 2C + \frac{\pi}{2}(D_1 + D_2) + \frac{(D_2 - D_1)^2}{2C} \tag{10}$$

Shaft diameter: The shaft diameter use for both the centrifugal blower and the reciprocating mechanism was determined based on bending and torsional stress which the shaft experienced[11,12] by using Eq. 12:

$$d^3 = \frac{16}{\pi S_s}\sqrt{(K_b\ M_b)^2 + (K_t\ M_t)^2} \tag{11}$$

Hopper capacity:

- Area of the square section = L^2
- The volume of the rectangular section = $L^2\times$depth
- The volume of the pyramidal section = 1/3 base area×height
- Total volume = volume of the rectangular section+volume of the pyramidal section

Design of centrifugal blower: The fan must be capable of providing the required air velocity necessary for cleaning and separation of the grain-impurity mixture. It was deduced by using Eq. 13:

$$Q = AV \tag{12}$$

where, A is the area of the blade and V is the actual velocity of air produced from the blower which was deduced taking into consideration the terminal velocity of the maize sample.

Determination of amplitude and frequency of vibration: For a system of force vibration with a single degree of freedom, the amplitude[13,14] is given in Eq. 14:

$$Y = \frac{\frac{F}{K}}{\left(\left(1-\left(\frac{w}{w_n}\right)^2\right)^2 + \left(2\left(\frac{w}{w_n}\right)^2\right)\right)^{0.5}} \tag{13}$$

where, F is the magnitude of excitation, K is the stiffness of spring, m is the mass of the system, is the coefficient of damping.

Machine operation: The grain cleaning machine was designed to separate maize from MOG. A 2 hp electric motor provides power to the reciprocating mechanism alongside the centrifugal blower through an arrangement of pulleys and belt as in Fig. 2. The reciprocating mechanism oscillated in a pendulum motion with the aid of an eccentric drive. The grain-impurity mixture from the hopper was adjustable. By gravity, the lighter impurities were blown off via the cushion of air coming from the blower as the grain terminal velocity is higher than that of the light impurities. Then subsequent cleaning took place in the screen assembly via the agitation produced by the eccentric drive. The clean grain was collected on the product outlet while the foreign material was collected at the reject outlet.

Preparation of samples: The samples taken for the experimental study were prepared from materials after threshing of maize. The 5.5 kg of the sample having three replications was cleaned manually to have the weight of the clean sample and MOG before the commencement of the experiment, which was taken to be 25% of MOG and 75% of the clean grain. The moisture content (MC_{db}) was determined to be 8%. It was stated that for 8% MC_{db} the terminal velocity[15] was 10.77 m sec^{-1} for *Zea mays* L. Varieties hybrid single cross (SC), which was planted in the Landmark University Teaching and Research Farm, (latitude 8°9°0″ N, longitude 5°61°0″ E), Omu-Aran, Kwara state, Nigeria. The samples were fed at a feed gate opening of 13.23, 24.94 and 33.06 mm at a predetermined sieve slope and oscillation.

Experimental design: The RSM was used to investigate the effect of air velocity (9.12-12.30 m sec^{-1}) and feed gate opening (13.23-33.06 mm) at a constant moisture content (8% db) on responses (separation efficiency, separation loss, cleaning loss and cleaning efficiency) by using a suitable central composite design (CCD).

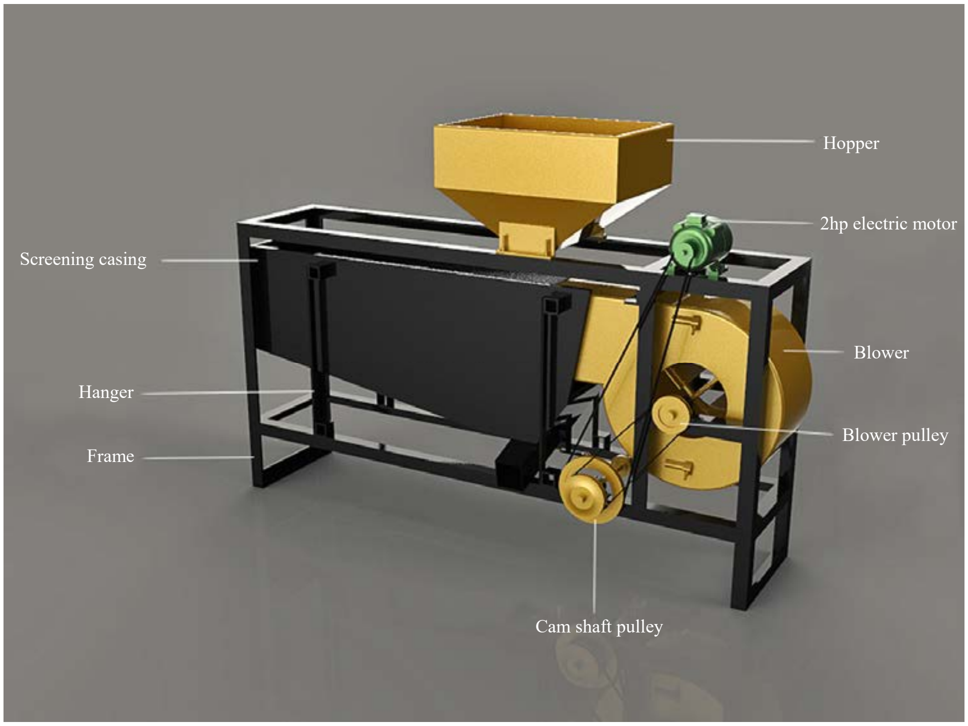

Fig. 2: Isometric view of the developed grain cleaning machine

Performance evaluation: The equation below was used for calculating the separation efficiency (SE), separation loss, cleaning efficiency (CE) and cleaning loss (CL) in percentage (SL)[16,17]:

$$\text{SE (\%)} = \frac{M_1}{M_2} \times 100 \tag{14}$$

$$\text{SL (\%)} = \frac{M_4 - M_3}{M_4} \times 100 \tag{15}$$

$$\text{CE} = \frac{M_{CSS}}{M_{SBC}} \times 100\% - \text{CL} \tag{16}$$

$$\text{CL (\%)} = \frac{S_1}{S_0} \times 100 \tag{17}$$

where, M_1 is the mass of impurities after separation and cleaning (kg), M_2 is the mass of impurities before separation and cleaning (kg), M_3 is the mass of grains after separation and cleaning (kg), M_4 is the mass of grains before separation and cleaning (kg), SE is the separation efficiency (%), SL is the separation loss (%), M_{CSS} is the mass of clean grain sample after separation and cleaning (i.e., M_3) (kg), MSBG is the mass of the sample before cleaning (kg), S_1 is the grain loss behind the machine (M_4-M_3 in kg, S_0 is the grain output (M_3 in kg, CE is the cleaning efficiency (%), CL is the cleaning loss (%).

Statistical analysis: The effect of air velocity and feed gate opening on the response was assessed. A second-order polynomial regression model for the dependent variables was established to fit experimental data for each response and was analyzed by using design expert software 11 (Statease)[18]:

$$y_i = a_0 + \sum_{i=1}^{b} a_i x_i + \sum_{i=1}^{b} a_{ii} x_{i^2} + \sum_{i=1}^{b}\sum_{i=1}^{b} a_{ij} x_i x_j \tag{18}$$

where, x_i (i =1, 2) are the independent variables (air velocity and feed gate opening) and a_0, a_i, a_{ii} and a_{ij} are coefficient for intercept, linear, quadratic and interactive effect, respectively. The statistical significance of the terms was examined by analysis of variance (ANOVA) for each of the performance efficiency examined. The adequacy of the regression model was checked by correlation coefficient R^2 and the p-value[18].

Optimization: The main objective of optimization was to maximize the desired quality and minimize the undesired one. The separation efficiency, separation loss, cleaning loss and cleaning efficiency were some of the parameters that determine the performance efficiency of the grain cleaner. Therefore, optimal conditions were determined for the operation of the grain cleaner based on these parameters. The targeted optimal values for separation efficiency, separation loss, cleaning loss and cleaning efficiency were 95.22, 1.903, 1.078 and 95.34%, respectively. The response surface of desirability function was used for the numerical optimization[18].

RESULTS AND DISCUSSION

Machine parameters: The results in Table 1 showed the model statistics and their significance. The regression models for separation loss (SL), cleaning loss (CL) and cleaning efficiency (CE) were significant ($p<0.05$), with correlation coefficients R^2 = 0.803, 0.799 and 0.814, respectively, whereas, the regression model for separation efficiency with correlation coefficient R^2 = 0.564 was not significant ($p>0.05$). There was a reasonable agreement between the predicted R^2 and the adjusted R^2. The adequate precision values were >4, indicating an adequate signal (i.e., adequate model discrimination) (Table 1). The effect of the feed gate opening and air velocity on cleaning loss, cleaning efficiency and separation loss were significant, but its effect on the separation efficiency was not significant as analyzed by using the Ducan multiple range test (Table 2). The fitted regression equations for the performance efficiencies given in Table 3 showed the response (model) of the various performance efficiencies to the combined effect of both the air velocity and feed gate opening.

Table 1: Analysis of variance and model statistics for performance efficiency of the developed grain cleaner

	Product response			
Variables	SE (%)	SL (%)	CL (%)	CE (%)
F-value	2.150	6.800	6.610	7.270
P>F	0.2119	0.0324	0.0343	0.0285
Mean	88.560	7.550	9.420	81.320
SD	9.010	5.730	8.730	13.530
CV	10.180	75.900	92.680	16.640
R^2	0.564	0.803	0.799	0.814
Adjusted R^2	0.3022	0.6852	0.6778	0.7016
Predicted R^2	-1.7474	0.0346	-0.0465	0.0400
Adequate precision	4.7123	7.5007	7.5051	7.6417

SE: Separation efficiency, SL: Separation loss, CL: Cleaning loss, CE: Cleaning efficiency, CV: Coefficient of variation, R^2: Coefficient of determination

Separation efficiency: The response surface plot showed in Fig. 3, which illustrated that the separation efficiency increased with an increase in the feed gate opening and a decrease in the air velocity. The result reported for the aerodynamic properties of flax seeds showed that the separation efficiency increased with a decrease in the feed rate and a corresponding increase in air velocity, which is not in concomitance with the phenomenal change experience in the above separation efficiency of maize-impurity mixture possibly due to the tilt angle or orientation of the screen casing[16].

Table 2: Result for the parameters at the different process variables with its coded values

FGO (mm)	AV (m sec^{-1})	SE (%)$^{\alpha}$	SL (%)$^{\infty}$	CL (%)$^{\Omega}$	CE (%)$^{\$}$
13.23(-1)	12.30(1)	61.71 ± 0.05^{a}	32.53 ± 0.13^{b}	48.22 ± 0.12^{a}	19.25 ± 0.02^{b}
	9.12(-1)	94.00 ± 0.13^{b}	2.54 ± 0.02^{c}	1.08 ± 0.15^{b}	92.45 ± 0.02^{c}
	10.21(0)	95.21 ± 0.03^{b}	4.00 ± 0.01^{a}	4.17 ± 0.02^{c}	86.53 ± 0.06^{a}
24.94(-0.5)	12.30(1)	94.23 ± 0.05^{b}	14.67 ± 0.11^{c}	17.19 ± 0.01^{a}	68.15 ± 0.04^{c}
	9.12(-1)	95.22 ± 0.12^{b}	1.90 ± 0.03^{a}	1.98 ± 0.04^{b}	95.34 ± 0.03^{a}
	10.21(0)	92.34 ± 0.06^{c}	1.91 ± 0.01^{a}	1.98 ± 0.03^{b}	95.32 ± 0.01^{a}
33.06(0)	12.30(1)	89.32 ± 0.01^{b}	5.60 ± 0.04^{c}	5.93 ± 0.08^{c}	88.47 ± 0.10^{b}
	9.12(-1)	82.86 ± 0.01^{c}	1.978 ± 0.05^{b}	1.90 ± 0.04^{a}	95.21 ± 0.03^{c}
	10.21(0)	92.13 ± 0.11^{b}	2.789 ± 0.03^{b}	2.35 ± 0.10^{a}	91.12 ± 0.04^{b}

$^{\alpha}$FGO×AV ($p>0.05$): Not significant, $^{\infty}$FGO×AV ($p<0.05$): Significant, $^{\Omega}$FGO×AV ($p<0.05$): Significant, $^{\$}$FGO×AV ($p<0.05$): Significant, Means followed by different superscripts are significantly different ($p<0.05$) along column according to Duncan multiple range test

Table 3: Fitted regression equations for the various performance efficiencies

Regression models	Findings	R^2
SE = 90.79+4.46FGO-4.47AV	The positive and negative coefficient for the linear terms of the feed gate opening and air velocity indicates that the separation efficiency increased with an increase in the feed gate opening and a decrease in the air velocity	0.564
SL = 2.76-9.569FGO+1.138AV-13.183FGO×AV	The positive coefficient for the air velocity in the fitted regression model suggests that an increase in the air velocity will increase the separation loss, while the negative coefficient for the feed gate opening represents a decrease in the separation loss as feed gate opening is increased	0.803
CL = 2.21-14.43FGO+0.288AV-21.554FGO×AV	The negative coefficient of the feed gate opening showed that an increase in the feed gate opening would reduce the cleaning loss; the positive coefficient of the air velocity suggests the cleaning loss increased with increase in the air velocity	0.799
CE = 94.08+25.523FGO-1.24AV+33.23FGO×AV	The cleaning efficiency which is a desirable quality increased with an increase in the feed gate opening and a decrease in the air velocity as shown by the positive and negative coefficient	0.814

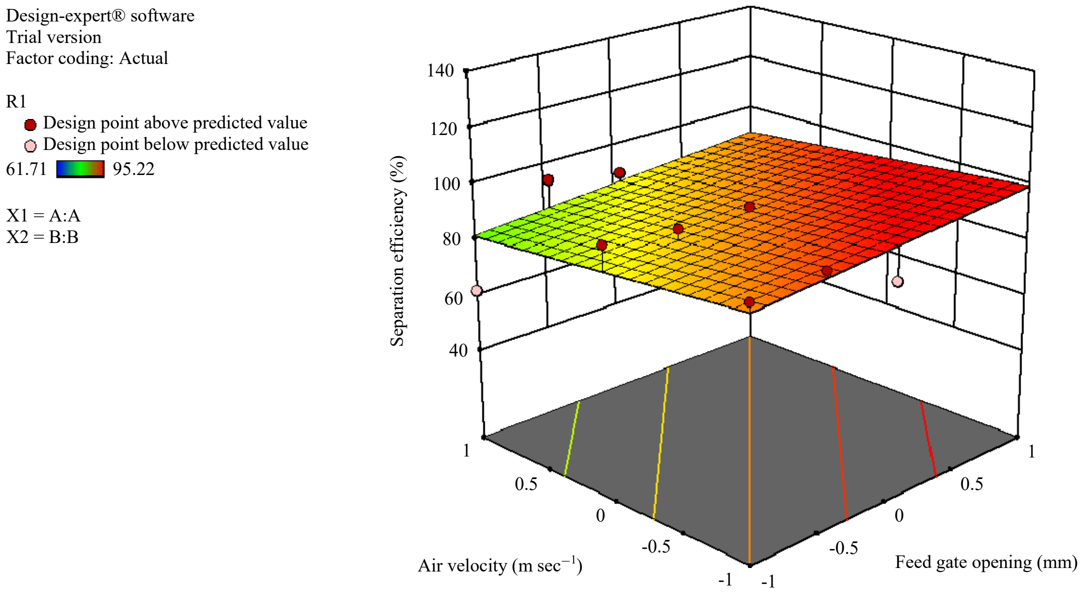

Fig. 3: Effects of the air velocity (AV) and feed gate opening (FGO) on the separation efficiency (SE)

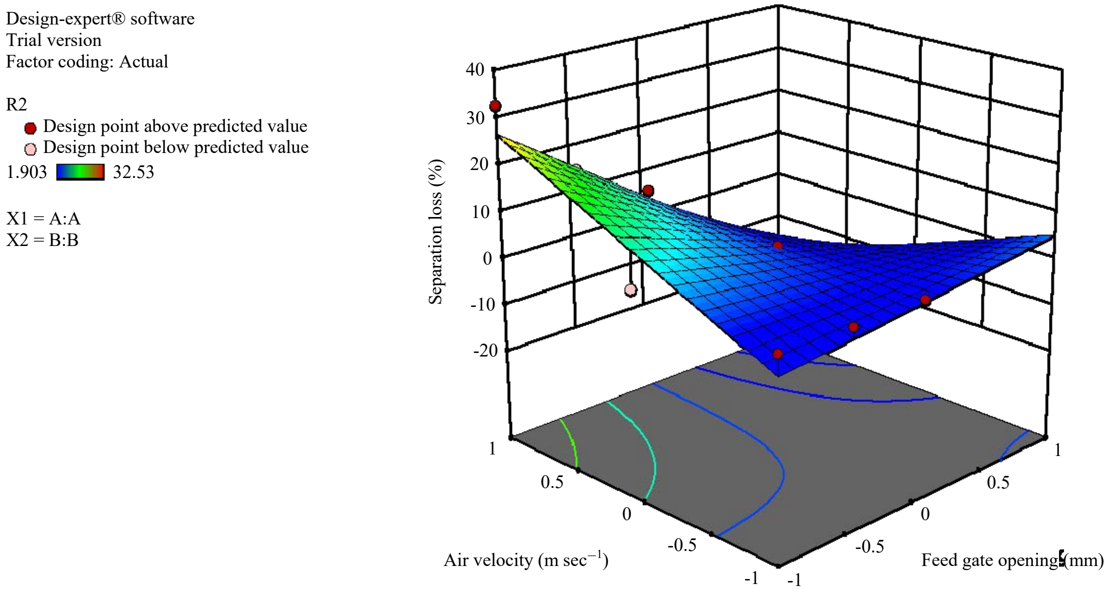

Fig. 4: Effects of the air velocity (AV) and feed gate opening (FGO) on the separation loss (SL)

Separation loss: The response surface plot for the separation loss with the two independent variables illustrated that the two variables has to be reduced to diminish the separation loss as shown in Fig. 4. It was reported by Ayman[19] that the separation loss is reduced with an increase in feed rate and a decrease in air velocity for flax seeds. This does not completely agree with current findings of the behavior of maize-impurity mixture with these variables.

Cleaning loss: The cleaning loss can be reduced if these two independent variables are simultaneously reduced as graphically illustrated in Fig. 5. The results reported by Usman *et al.*[19] on the percentage loss for paddy rice increasing with an increase in air velocity and feed rate is in agreement with current finding. While Simonyan and Yiljep[20] reported in their work that the cleaning loss for sorghum increased with an increase in the feed rate and air velocity, which is also in agreement with current finding.

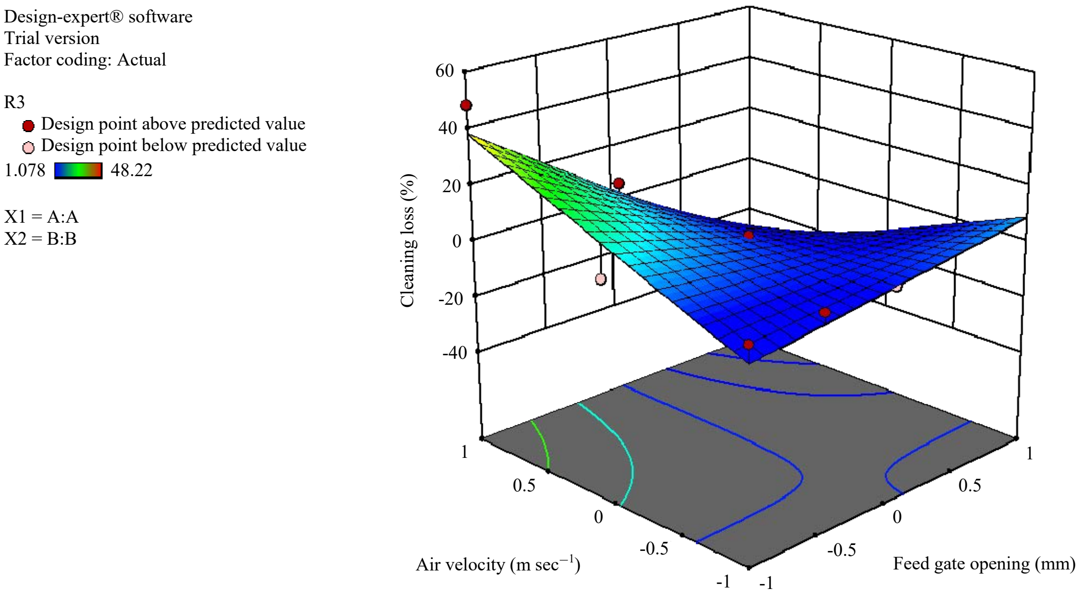

Fig. 5: Effects of the air velocity (AV) and feed gate opening (FGO) on the cleaning loss (CL)

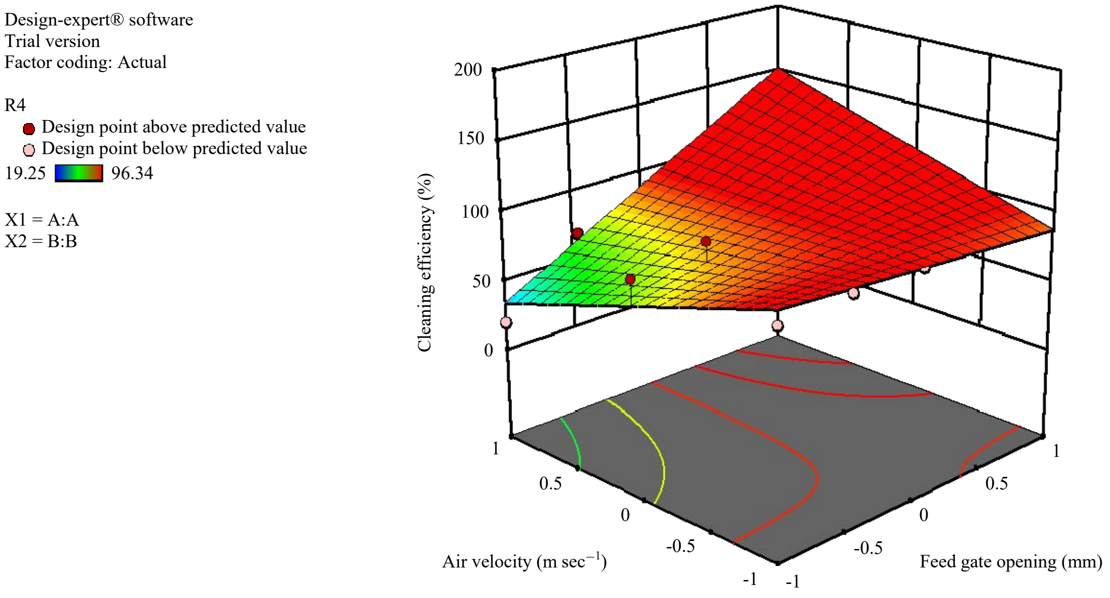

Fig. 6: Effects of the air velocity (AV) and feed gate opening (FGO) on the cleaning efficiency (CE)

Cleaning efficiency: The response surface plot of the cleaning efficiency versus the two independent variables in Fig. 6. It further illustrated that the cleaning efficiency is increased with an increase in the feed gate opening and decrease in the air velocity. A similar result was reported by Muhammad *et al.*[21] for the effect of air velocity on the cleaning efficiency for millet, sorghum and soybean, but an inverse result was also reported on the effect of feed gate opening on the cleaning efficiency. While Usman *et al.*[19] in their experiment on a winnower for paddy rice reported that the cleaning efficiency increased with a decrease in the feed rate and a decrease in the air velocity, this agreed to the findings of current study that cleaning efficiency increased with decrease in air velocity, but does not agree to current finding that cleaning efficiency increased with an increase in feed gate opening for maize. In the research reported by Simonyan and Yiljep[20], they stated that the cleaning efficiency for sorghum reduced with an increase in the feed rate.

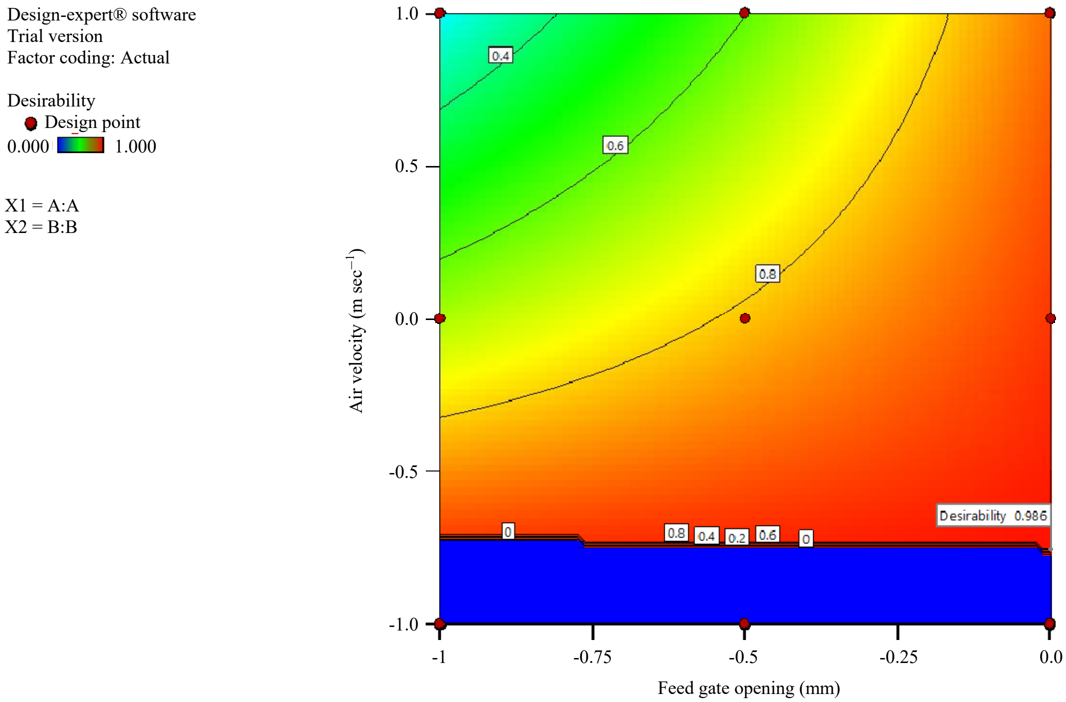

Fig. 7: Desirability function response surface for performance efficiency of the developed grain cleaner

Optimization: The optimal performance efficiencies were obtained by using the desirability function method. The desirability value obtained was 0.986 as shown in Fig. 7.

CONCLUSION

Grain cleaning continues to inflict drudgery on the rural dwellers who are directly engaged in the business of maize farming. To combat this pertinent issue a prototype grain cleaning machine was developed. Response surface modeling revealed the significant effects of two independent variables (feed gate opening and air velocity) on some of the performance efficiency (separation loss, cleaning loss and cleaning efficiency) of the developed grain cleaning machine, but there was no significant effect of these variables on the separation efficiency.

SIGNIFICANCE STATEMENT

This study provides an improvement on the grain cleaner, optimizes some of the conditions necessary for grain cleaning (feed gate opening and air velocity) and studied some of the responses of performance efficiency parameters like, separation efficiency, separation loss, cleaning loss and cleaning efficiency to the above-mentioned variables. This new improvement offers the rural farmers an alternative grain cleaner which can help reduce the drudgery associated with manual cleaning of grains.

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